Mechanical Design of the Crosstrack Infrared Sounder (CrIS)

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ABSTRACT

The mechanical design characteristics of the CrIS sensor module is presented. Several structural and thermal challenges are addressed. An 8-cm optical system, which includes a scanner, interferometer, 25-cm focal length telescope, aft optics, and cooler, efficiently use the available volume (0.158 m^3). The sensor manages 90 Watts of electronic dissipation while maintaining a stable radiometric environment. It uses multi-stage passive cooling to provide 81 K focal plane and 220 K aft optics temperatures for low-earth orbits at up to 90-degree orbit normal-to-sun angles. Structurally, the interferometer scanning mirror maintains pointing accuracy of less than 20 microradians in the presence of self-induced and external disturbances.

Keywords: mechanical design, sounder, remote sensing, thermal control

1. BACKGROUND

In the early 1990s a new low earth orbit (LEO) meteorological satellite (METSAT) program was initiated. Contracts for instruments for the new system, known as NPOESS (National Polar-orbiting Operational Environmental Satellite System) began in 1997. The Crosstrack Infrared Sounder (CrIS) is one of the primary instruments within the NPOESS system. Its mission is to collect upwelling infrared spectra at very high spectral resolution, and with excellent radiometric precision. This data is then merged with microwave data from other sensors on the NPOESS platform to construct highly accurate temperature, moisture, and pressure profiles of the earth's atmosphere. Collectively, the CrIS and microwave sensors are referred to as the CrIMSS (Crosstrack Infrared and Microwave Sounding Suite). The profiles produced by this suite are a primary input to numerical weather forecast models, and their improved accuracy offer enhanced forecast accuracy on a global basis.[1]

The early conceptual design of the CrIS began as part of a Phase 1 study funded by the NPOESS Integrated Program Office (IPO). The objective of this study program was to develop a "best value" approach for the instrument, including algorithms, and conduct numerous risk-reduction demonstrations to address specific CrIS risk areas. A Preliminary Design Review in April 1999 completed the Phase 1 activities. The Phase 2 program is now underway, with delivery of a flight sensor scheduled by 2004.

The purpose of this paper is to describe the mechanical engineering aspects of the CrIS instrument, discuss the key trades that led to the selection of the CrIS mechanical architecture, and provide details on some of the mechanical risk-reduction activities that have been conducted to prove the feasibility of the CrIS design.

2. CrIS MECHANICAL DESIGN OVERVIEW

As illustrated in Figure 1, CrIS is a compact cross-track scanning instrument. Its key subsystems include a step and settle scene selection model, a full-aperture internal calibration source, a large-aperture Michelson interferometer, a three-element all reflective telescope, a cooled aft optics enclosure which creates three spectral bands, a multiple-stage passive cooler, and an attached electronics assembly. The instrument thermal control is completely self-contained. All internally-dissipated electrical heat is managed by instrument radiators. The subsystems with critical alignment requirements are co-located on an optical bench. Less critical alignments and the spacecraft interfaces are controlled by a larger instrument frame, which is the primary structural element within the instrument.

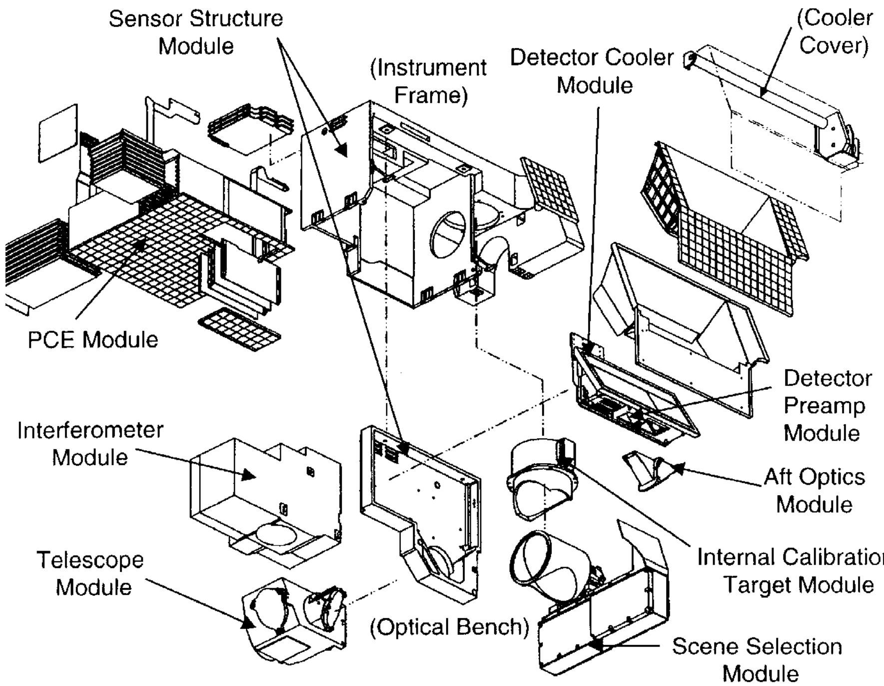


Figure 1. Mechanical Architecture of the CrIS Instrument

3. CRIS TRADE STUDY RESULTS

Since its inception, the primary objective of the CrIS program has been to deliver the highest-quality data products possible, and the smallest and lightest sensor possible, while meeting aggressive cost constraints. Many of the mechanical requirements have been driven by the results of many cost-versus-performance trade studies were conducted to select the best combination of values for the CrIS system. The most fundamental study affecting the mechanical design was the examination of the cost and performance of different sensor aperture sizes. Larger apertures tend to improve performance by increasing the sensitivity of the sensor (or improving its signal to noise ratio while viewing the atmosphere), which in turn improves the final data product performance. However, larger apertures also tend to be more expensive, due to the larger size of optical elements and support structure.

The cost-versus-performance results of the trade are shown in Figure 2. A clear “knee in the curve” becomes apparent at an aperture size of about 10 cm, and given no other constraints, this would have been our chosen aperture for CrIS. However, volume constraints imposed by spacecraft packaging considerations, and CrIS layout studies found that this volume constraint limits the available aperture to approximately 8 cm. Thus, the trade study determined that an 8 cm aperture was optimum for CrIS. The aperture and other trade study results that affect the mechanical architecture of the CrIS sensor are summarized in Table 1.[1] Other important design drivers as illustrated by the trades in Table 1 are the selection of passive cooling, scanner and interferometer configurations, location of optical subsystems such as the telescope, and the operating temperatures of the optical subsystems.

Table 1. Key CrIS Trade Study Results

Trade Study	Results and Justification
Active vs. Passive Cooler	4-stage passive cooler selected. Active coolers are higher cost, higher risk, lower reliability,and offer only minimal EDR performance improvements
Number of Bands	3 spectral bands selected for maximum EDR performance robustness
Barrel-Roll Versus Paddle Wheel Scanner	Baseline barrel-roll scanner is higher performance (due to larger allowable aperture and improved calibration) and lower cost

Telescope Before / After Interferometer	Telescope after interferometer permits larger aperture and higher performance with virtually no cost impact
Flat Mirror Versus Cornercube Interferometer	Cornercube system is slightly lower performance due to smaller aperture; slightly higher risk due to tight cube thermal stability requirements; slightly higher cost
Telescope Cooling	Ambient-temperature telescope has negligible impact on NEdN; reduces cost through elimination of second passive cooler
Aft Optics Mounting	Mounting aft optics dichroics directly to first stage of passive cooler improves coregistration performance at no added cost
Centralized Versus Distributed Power Supplies	Cost reductions and thermal advantages in combining PCE and interferometer power supplies

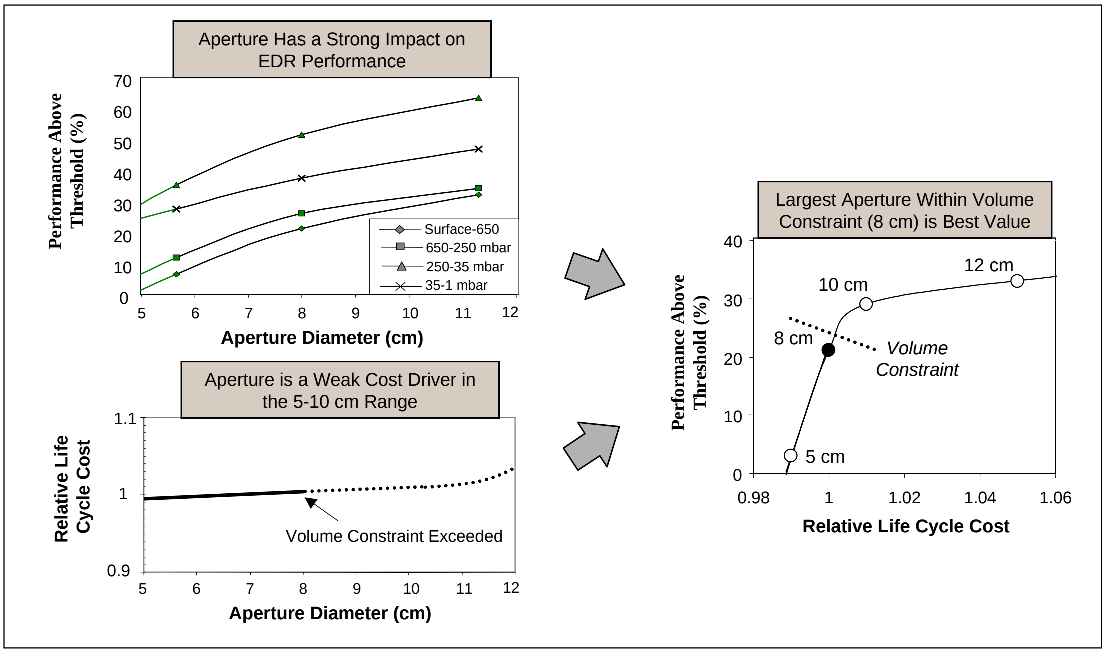


Figure 2. CrIS Aperture Trade Study

After the completion of the trade studies a conceptual description of the instrument and its module was formulated. The general relationships between the modules are established and detailed design activities began. A mechanical block diagram illustrating the structural and thermal interrelationship between the modules is shown in Figure 3.

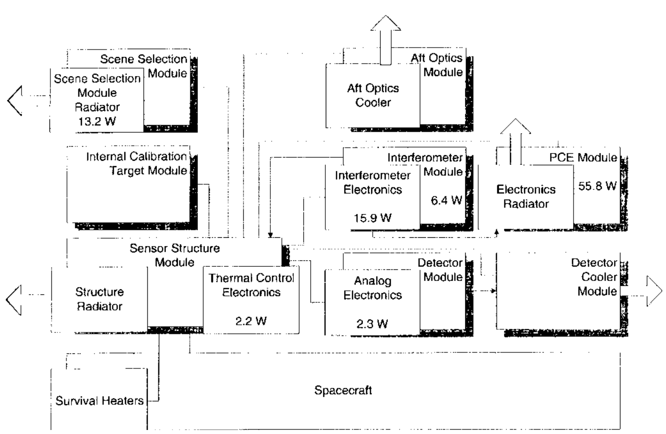


Figure 3. CrIS Instrument Thermal and Structural Block Diagram

4. CRIS MECHANICAL REQUIREMENT ALLOCATION

After the completion of the trade studies defined the design configuration, a significant effort to allocate system requirements to the subsystems or modules followed. The key requirements identified in the governing system specification were parsed into first the sensor specification and next the modules specifications. Most of the critical structural and thermal instrument requirements have been allocated to the sensor Structure Module. Two key functions of this module are the static and dynamic alignment control and the thermal control of the entire instrument. Also included are the spacecraft interface allocations.

Requirement trees for all major specification categories were constructed, that trace the requirements from the top-level system allocations down through the modules with the resulting derived requirements documented into the module specifications. Sample trees include Mass, Power, Initial Alignment, Thermal Control, Resonant Frequency, NEdN, Radiometric Uncertainty, and Spectral Uncertainty. A much more thorough treatment of this subject is found in Reference 2. Mechanical requirements show up in a number of these trees. A good example is the Thermal Control Tree, which is shown in Figure 3. The allocated radiative and conductive heat transfer between modules is shown as well as the internal dissipation and external sources of heat input.

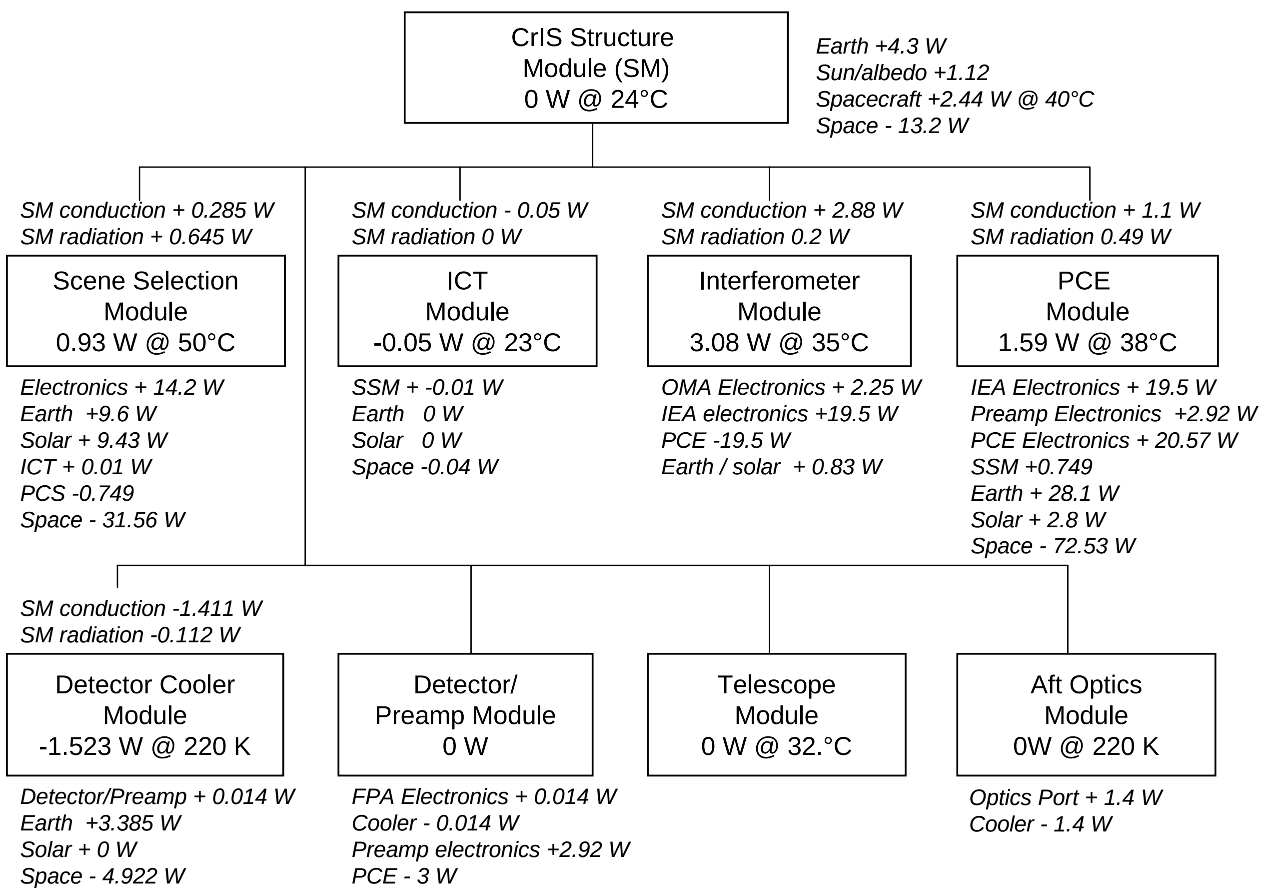


Figure 3. CrIS Instrument Thermal Control Allocations

5. CRIS INSTRUMENT THERMAL AND STRUCTURAL CONTROL CONSIDERATIONS

As identified in the thermal allocation chart shown above, there are several thermal control challenges for the CrIS instrument. It is required to be self-regulating despite dissipating 91 W of electrical power, while mounted on a spacecraft that varies in temperature from -10 °C to 40 °C. At the same time, its radiometric performance depends on a stable, low temperature background to minimize noise sources. This is accomplished in two ways. First, almost all the heat dissipating components are thermally decoupled form the optics modules. The scanner electronics heat is removed by radiators within the SSM module, and most of the remaining electronics heat is isolated to the PCE, which also has its own radiators. The only remaining heat is from the interferometer, which comes mostly from the laser metrology subsystem and mirror drive actuators. This heat which totals approximately 5 W is used to help maintain the temperature of the instrument frame. By careful selection of the spacecraft and PCE support flexure thermal properties, it is possible to operate the optical structures within the instrument uncontrolled. Within the 50 °C operating range of the spacecraft, the instrument optics operate within a relatively comfortable –5 °C to 20 °C range. The range mostly depends on which orbit is selected for the spacecraft. The orbital average temperature change within the instrument is much less, on the order of 2 °C. Comprehensive thermal modeling has resulted in the ability to completely characterize the instrument thermal performance over any orbital condition. Critical temperatures and gradients and gradients are calculated for use in the thermal and radiometric performance models. A sample of the output is illustrated in Figure 4, which shows the expected temperature distribution of the instrument frame and orbital stability of the optical bench structures.

Another very critical performance characteristic is the operation of the instrument, particularly the interferometer, in a dynamically active spacecraft environment. Detailed finite element models for all modules have been constructed so that the dynamic interactions can be evaluated. Preliminary results show that the effects of spacecraft disturbances on the critical mechanisms are manageable, and that the disturbances generated within the CrIS instrument meet the specified limits for

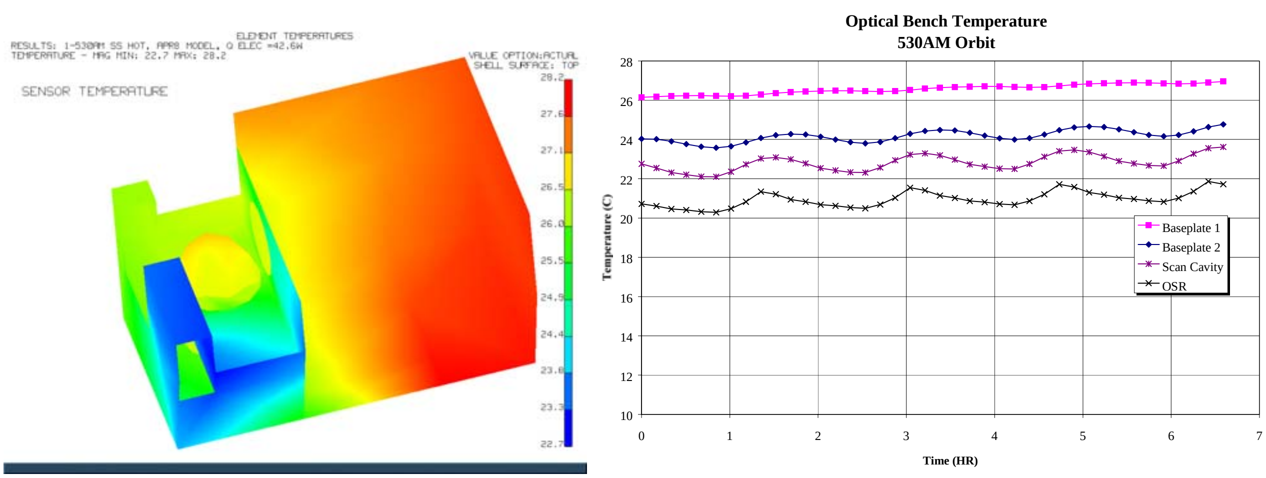
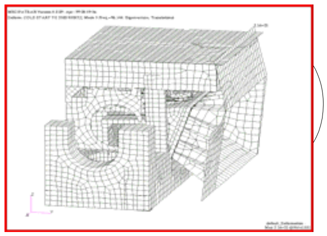
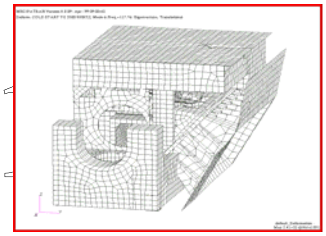


Figure 4. CrIS Instrument Thermal Modeling for Temperature Distribution and Stability

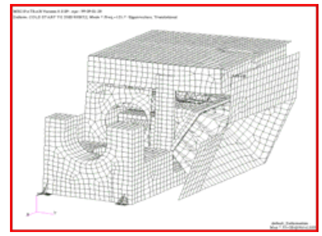
disturbance output identified in the interface requirements. The approach used is to produce high frequency structures that are insensitive to low frequency disturbances, and to implement isolation at the higher frequencies. The use of detailed finite element modeling and analysis tools permits the characterization and implementation of stable structures. The first primary structural mode is at over 100 Hz, and isolation in the current baseline design is for frequencies above 300 Hz. The first several modes for the instrument design are illustrated in Figure 5. The spacecraft for the mission is not yet selected, so detailed interfaces and key structural frequencies are not yet defined. To accommodate these interfaces following spacecraft award, the CrIS instrument has considerable design flexibility built into the design. The flexure structural properties have been shown in our sensitivity analyses to have a large effect on the frequency characteristics of the structure. They can be tailored at the spacecraft-to-instrument frame interface, at the instrument frame-to-optical bench interface, and at the instrument frame-to-PCE interface to select structural resonances. In effect, they can be altered to be decoupled from critical spacecraft frequencies.



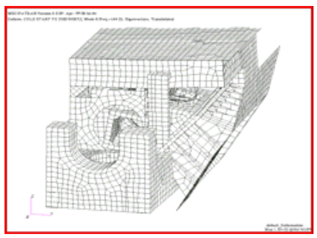
Mode 2 96 Hz
Detector Cooler



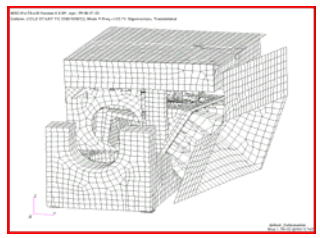
Mode 3 118 Hz
Optical Bench



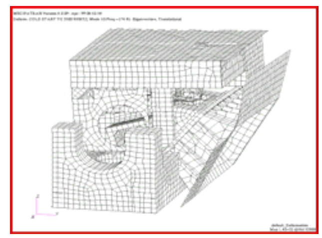
Mode 4 122 Hz
Mounting Flexures



Mode 5 144 Hz
Optical Bench (X)



Mode 6 153 Hz
Detector Cooler



Mode 7 175 Hz
Interferometer/Cooler

Figure 5. CrIS Instrument Primary Structural Modes

6. CRIS MODULES

The functional partitioning and associated requirement allocation led to the development of the CrIS modules. Each has been selected to simplify interfaces which benefits both the producability and testability of the design. Many of the requirements can be tested at the module or sub-assembly level. For example, all critical instrument alignments can be performed and verified at the optical bench level in parallel with other instrument integration activities. Minimal instrument testing is planned at the bench level since most modules interfaces are verified as part of the module test programs.

The system volume limit, the thermal stability, and the structural stability were the key design drivers for all the modules. A short description of each one, identifying the key features and design challenges, follows.

Sensor Structure: The primary structure of the instrument is composed of two major assemblies, the instrument frame and the optical bench. As noted earlier, all critical alignments are maintained by this bench. It includes the module interfaces for the interferometer, telescope, and and aft-optics/detector cooler. This encompasses the entire optical path except for the scene selection. The bench structure is a beryllium plate that is stiffened to support approximately 26 kg. Each module is kinematically supported. Very little thermal dissipation is permitted to be conducted or radiated into or through the structure to preserve its stability. It also supports the instrument alignment cube to minimize the number of mounting interfaces coupled into the spacecraft/sensor line-of-sight reference.

The optical bench assembly is in-turn kinematically mounted to larger structure, referred to as the instrument frame. This is an aluminum-beryllium composite structure that links the Scene Selection module to the optical bench. It also includes flexure mounts to the spacecraft that serve a dual purpose. They accommodate a large temperature difference between the spacecraft and instrument and provide for high frequency vibration isolation from spacecraft sources. The thermal control of the insturment, especially the Internal Calibration Target, is maintained by the instrument frame. A small radiator is positioned on the anti-sun side to keep temperatures low during the maximum heating condition identified in the system specification. It also provides a low-thermal-conductance supporting structure for the Process and Control Electronics module. The hardware used to implement the instrument frame and optical bench is demostrated in Figure 6.

Scene Selection Module: A critical CrIS function is to direct energy into its optical modules. In addition to scene energy from the earth's atmosphere, calibration sources are also required. The Scene Selection Module (SSM) consists of a a 13.8 cm beryllium scan mirrir, a servo-controlled cross-tracking, step-and-settle positioning system. The earth scene consists of

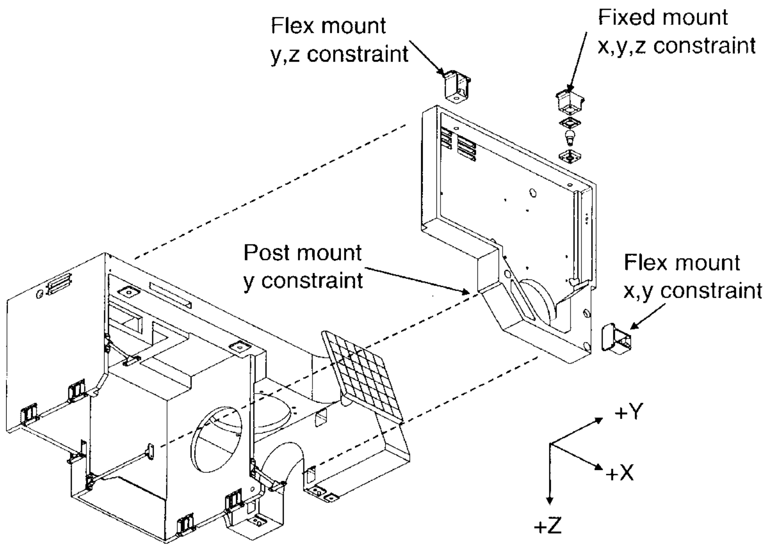


Figure 6. CrIS Instrument Frame and Optical Bench Structures

30 mirror positions centered about nadir. Two calibration sources are provided including a cold-space view off the limb of the earth and a warm target whose temperature is controlled by the sensor. To view the earth and both targets requires most of an entire rotation, hence the return to start is accomplished by completing the rotation at an increased rotational velocity. The scan system, which is being built by Ball Aerospace, also includes an in-track velocity compensation. This second servo system is driven by a linear motor through flexures. It is a self-contained module that provides its own drive electronics and manages its own heat via an included radiator. The mounting interface between the instrument frame and the SSM has been selected to minimize the dynamics of the module by balancing the mass of the electronics with the mass of the motor/mirror assembly as shown in Figure 7.

Internal Calibration Target: To increase the accuracy of the instrument calibration, an internal warm target provides a second calibration reference. Its fundamental requirement is for temperature stability and uniformity. A high thermal capacitance in the target is achieved by a massive aluminum substrate that is shielded from external loads to the maximum extent possible. A barrel baffle has been added to the scene selection module to provide much of this shielding. The target is well coupled to the instrument frame, which has been designed for high thermal stability at the ICT mounting location, and the target is well-insulated from external influences. The target development is the responsibility of BOMEM, a division of ABB corporation. The target components are illustrated in Figure 8.

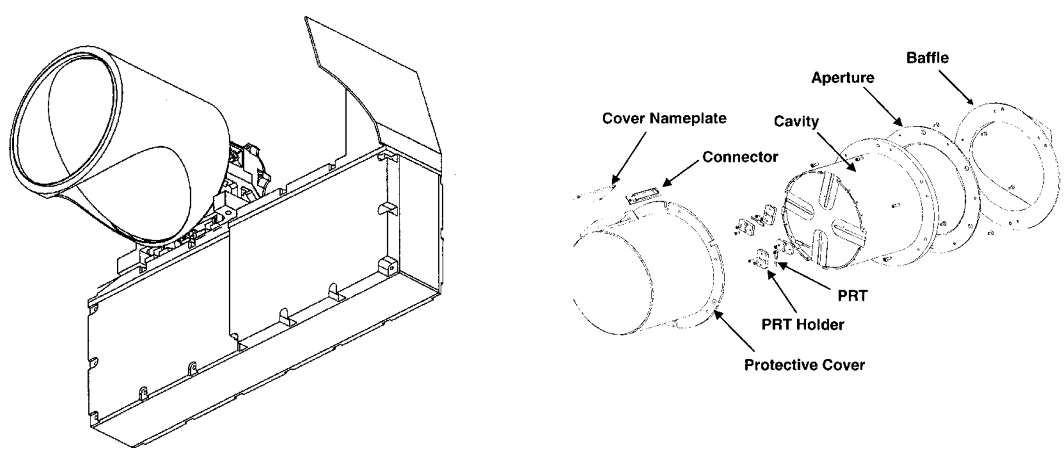


Figure 7. CrIS SSM Module **Figure 8. CrIS Internal Calibration Target**

Interferometer: The Michelson interferometer, also developed by BOMEM, is the first optical module following the SSM. It is also the first of the critical-alignment modules that is supported from the optical bench within the instrument frame. The beamsplitter and accompanying compensator are positioned at an incidence angle of 30 ° from the incoming energy. The refracted portion of the beam continues to a moving mirror that modulates the energy and reflects it back to be recombined with the reference beam. The moving mirror is supported by a balanced "porch-swing" mechanism that uses stiffened blade flexures that provide precise tracking. The blade flexure assemblies include adjustments that are used to tailor the assembly to remove most of the assembly tilt error of the scanning mirror. The balance is efficiently performed by using the mass of the rotor as counterweight for the moving mirror assembly. Beryllium, with its high stiffness and low mass, is used for many of the mechanism components to maximize its dynamic performance. The reference mirror includes a two-axis servo control system to dynamically compensate for residual tilt errors between the reference and modulated energy beams. The reference required to monitor and maintain the mirror alignment is provided by an included laser metrology subsystem, augmented by ultra-stable neon lamp calibration sources[3]. It uses a laser diode to produce a source of known wavelength, which is monitored by sensors that detect velocity and tilt errors within the system that are used to develop feedback control. The components that comprise this module are shown in Figure 9.

Telescope: A two-element (with an internal steering element) telescope is responsible for collecting the collimated interferometer output into a converging source for eventual collection by the system focal planes. The module also includes additional optical elements. Optical refraction within the interferometer introduces spectral shifts within its output energy. The first element at the entrance to the telescope module is a wedged rear-surfaced mirror that corrects for the spectral shift induced by the interferometer. That mirror directs the collimated energy to the primary mirror, which condenses the beam to a folding flat that directs it to the large secondary mirror which focuses the energy at an effective focal length of 254 mm. The innovative spider structure that holds the central folding flat minimizes obscuration in two orthogonal axes, as required by the design that rotates the optical output by 90 °. Before the energy is passed to the spectral separation (aft) optics, however, a contamination-prevention window is incorporated into the module. Since the aft optics are cooled to 220 K, an element and associated molecular contamination traps that provide a barrier to the cooled optics are needed. The final element is another folding flat the directs the now-focusing beam into the aft optics and cooler. Figure 10 shows the telescope module and its elements.

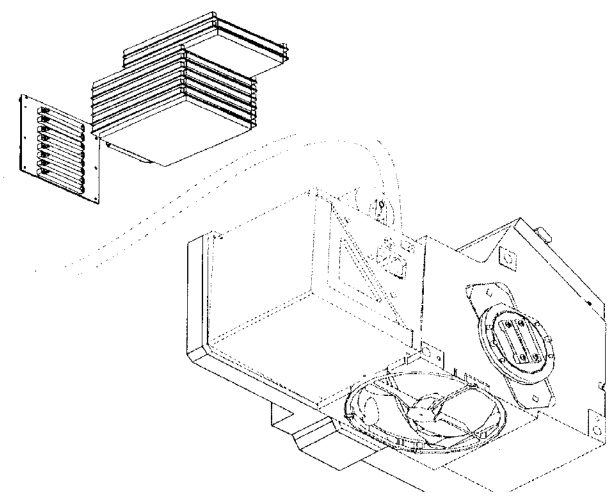


Figure 9. CrIS Interferometer Module

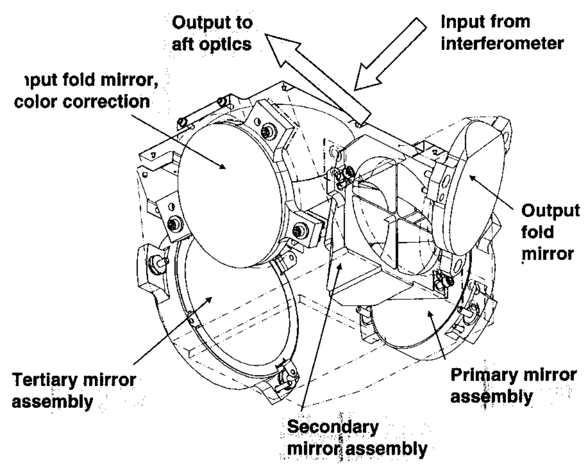
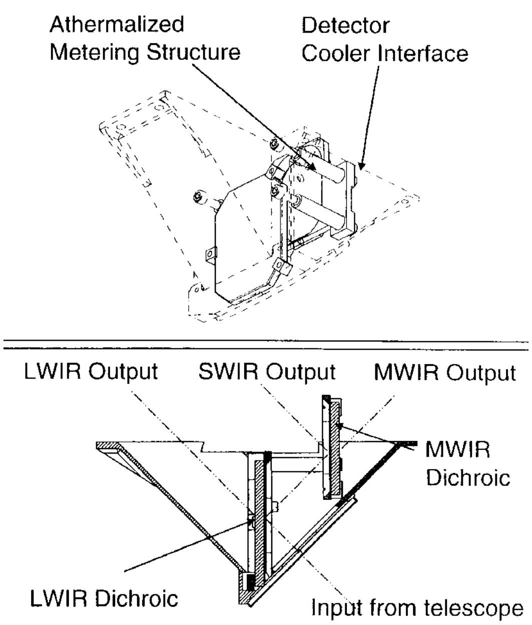


Figure 10. CrIS Telescope Module

Aft Optics: From the scan mirror, through the interferometer and telescope, all spectral channels are contained within a single beam. Only after reaching the aft optics, does the spectral separation of the beam into three disinct spectral bands

LWIR (650-1095 cm^{-1}), MWIR(1210-1750 cm^{-1}),, and SWIR(2155-2550 cm^{-1}) occur. This is accomplished by two dichroic elements that first remove the MWIR and SWIR via reflection from the beam and reflect the SWIR from the MWIR. There are several interesting aspects to the design. First is that they are configured in a manner to use minimum volume. The output focus locations for each beam are staggered, such that the interfacing focal planes occupy three separate planes. Making the focal planes coplaner requires a significant increase in the telescope focal distance that reduces the maximum system aperture that can be packaged in the available instrument volume. A second design driver is the large temperature range over which the elements must operate. The dichroics and the surrounding housing is cooled to reduce radiometric background noise into the focal planes. This is accomplished by mounting the assembly onto the first stage of the passive cooler. Since instrument co-registration is set with the cooler first stage at room temperature, the dichroic support system needs to maintain to optic positions over a temperature range of over 70 Celsius degrees. The design accomplishes this by implementing a bi-metallic metering structure. The components making up the aft optics are shown in Figure 11.

<u>Focal Plane Cooler</u>. A critical CrIS design selection was the use of photovoltaic (PV) detectors in all three spectral bands. PV detectors have the important benefits of higher sensitivity and much better non-linearity, however, they also place demands on the passive cooler because they require somewhat colder operating temperatures, especially in the LWIR. An earlier trade study indicated that adequate EDR performance can be obtained with warmer MWIR and SWIR focal plane temperatures as long as the critical LWIR focal planes temperature is minimized. The solution employed in CrIS is the implementation of multiple cooling stages. This permits the reduction of the thermal load on the LWIR stage by placing the MWIR and SWIR focal planes on a warmer, intermediate stage. In all there are four stages. The first one directly interfaces to the instrument optical bench and includes the reflective earthshield. The earthshield is configured to block the view from the focal plane emitters to high-flux external heat sources, namely the earth and sun. Its surfaces, while increasing the effective view to cold space, do introduce a significant heat load to the coldest stages, however, since there is a large view from them. It is therefore important to reduce their temperature, which is accomplished by a large emitter which permits operation at around 220 K. A second intermediate stage is required for the focal plane stages to reach their operating temperatures (98K for the MWIR and SWIR focal planes and 81 K for the LWIR). The design also includes a deployable contamination shade, developed by STARSYS corporation. The shade remains over the emitter surfaces for the first several weeks after launch while the contaminants resulting from initial outgassing dissipate. The configuration of the cooler stages and earthshield are illustrated in Figure 12. A thermal balance summary of the cooler is listed in Figure 13.



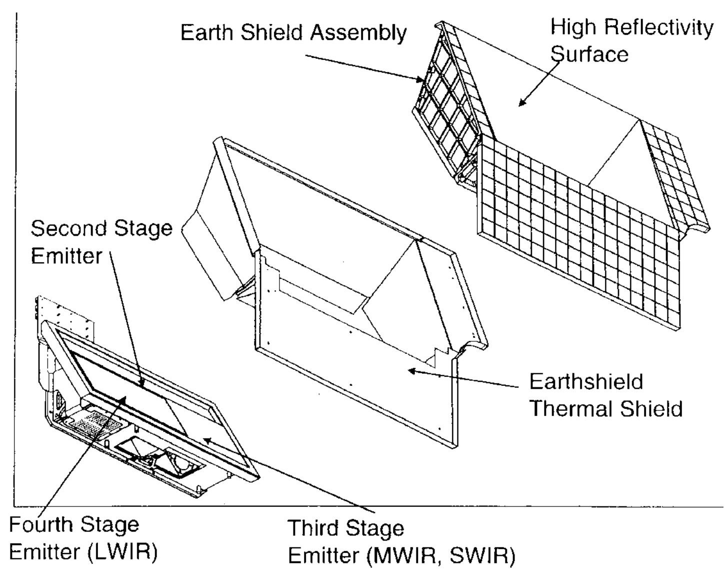


Figure 11. CrIS Aft Optics (Spectral Sparation) Module

Figure 12. CrIS Cooler Module

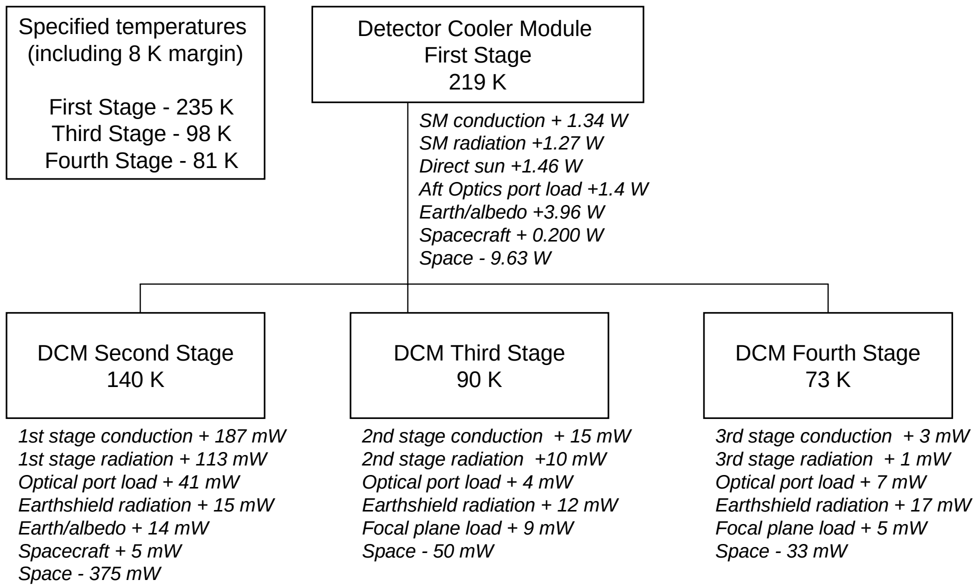


Figure 13. CrIS Detector Cooler Thermal Load Distribution and Capability Summary

Process and Control Electronics (PCE): All of the CrIS electronics are contained within the instrument simplifying integration at the spacecraft level and reducing total system mass. This presents a thermal challenge, however, as the opto-mechanical instrument must manage the entire electronics thermal load. CrIS accomplishes this by supporting the electronics in a thermally isolated module supported from the instrument frame by titanium flexures. Over 60 W of heat is dissipated in the module that includes a series of radiators to reject it to space. A large earth-facing radiator handles most of the load, with additional capacity in a smaller space-facing surface that is adjacent to the detector cooler first stage emitter. High density packaging of the circuit boards is required. Standard 3U and 6U configurations are used for most circuit cards and compact PCI connectors are used to accommodate the high interconnection density. Circuit card stiffeners and edge wedge clamps are required to maintain structural and thermal margins for the large circuit cards. Figure 14 illustrates the CrIS PCE configuration .

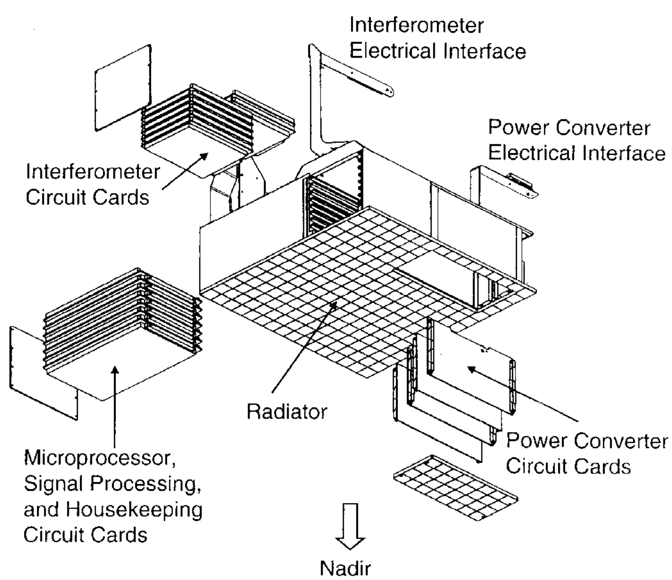


Figure 14. CrIS Process and Control Electronics Module

7. CRIS DEPLOYMENT PLANS

CrIS is expected to be one of the sensors onboard the planned NPOESS Preparatory Project (a joint NASA / NPOESS flight demonstration program). The CrIS near-term schedule is driven by the delivery date needed to support this flight mission. Current plans call for completion of a second-generation prototype sensor (designated EDU2) to be built and tested as a risk reduction measure just prior to CDR. This is followed by construction and test of the first flight unit (which will be a proto-qual unit) in early 2004, followed by additional flight units at 12-18 month intervals.

8. ACKNOWLEDGEMENTS

The author gratefully acknowledges the guidance and support of the NPOESS Integrated Program Office (IPO) which directs the CrIS program, In addition a talented and dedicated CrIS team at ITT Industries and other team member locations contributed to the development of the CrIS mechanical design. Team members include Bomem (a unit of ABB Inc.), Boeing North American, Ball Aerospace Systems Division, and Atmospheric Environmental Research, Inc.

9. REFERENCES